Chapter 2
Socio-economic and Environmental Implications of Renewable Energy Integrity in Oman: Scenario Modelling Using System Dynamics Approach

Aisha Al-Sarihi and Hafiz Bello

Abstract Oil and gas resources have played crucial role in boosting Oman's economy as well as meeting domestic energy needs. However, increasing domestic energy demands have created pressure on national energy supplies and made the search for alternative energy sources such as renewables ever more important. Aware of this challenge, investors, researchers and government have developed few renewable energy (RE) initiatives. However, RE accounts for less than 1% of total power generation in Oman. Importantly, socio-economic and environmental implications of RE, which could boost its uptake, are still under-researched. Using system dynamics approach, this chapter develops four RE integrity scenarios – i.e. business-as-usual, moderate, advanced and ambitious – and examines its long-term implications on economy, society and environment. The findings gained from long-term energy scenario analysis reveal that, under moderate, advanced and ambitious scenarios, new renewable energy jobs can be created by 2040 and natural gas consumption for electricity generation was estimated to decline by more than 60% by 2040 compared to the business-as-usual scenario. If no renewables are considered in the future energy mix, however, the total CO_2 emissions are expected to significantly rise by 2040 compared to 2010.

Keywords Oman · Fossil fuels · Renewable energy · Fuel mix · Scenarios · System dynamics · Socio-economic · Environmental implications

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1 Introduction

Like its neighbouring countries of the Gulf Cooperation Council (GCC) – Bahrain, Kuwait, Qatar, Saudi Arabia and the United Arab Emirates – Oman's economy has been highly reliant on oil and gas export revenues. Since their discovery, fossil fuel resources, namely, oil and gas, have been accounting for nearly 99% of total energy mix to meet the domestic energy needs. In recent years, however, the GCC states have exhibited signs of unsustainable[1] energy use such as energy security associated with increasing domestic energy demands and increasing per capita carbon emissions due to heavy reliance on fossil fuels. Despite GCC's vast resources of renewable energy, the use of renewable energy in total electricity installed capacity did not exceed 1% of total power capacity in 2014 (El-Katiri 2014; IRENA 2016).

The abundance of oil and gas resources has restricted the attention of investors, researchers and governments to develop alternative energy sources such as renewables. However, in recent years, research on the development and implication of renewable energy in the GCC countries is continuously growing (Alawaji 2001; Al-Karaghouli 2007; AER 2008; Bilen et al. 2008; Nalan et al. 2009; Chiu and Chang 2009; Ghorashi and Rahimi 2011; Al-mulali 2011; Anagreh and Bataineh 2011; Bataineh and Dalalah 2013; El Fadel et al. 2013). One of the key challenges, however, facing many of the regional countries is the lack of structured tool to aid a systemic account of energy policy and planning. The only recognised tools that have been attempted to aid energy planning in GCC countries are Long-range Energy Alternatives Planning (LEAP) system (El Fadel et al. 2013), Energy-Economy-Environment Modelling Laboratory (E3MLab) (Fragkos et al. 2013), panel data analysis model (Al-mulali 2011; Arouri et al. 2012) and techno-economic modelling of PV/battery systems (Al-Saqlawi 2017).

While some of these models are capable of giving valuable insights into analysis of energy demand and supply in an *economy*, they are, however, not able to account for the dynamics relating to connecting the power sector with *society* and the *environment*, since they are largely based on a static economic modelling approach. Indeed, Al-Saqlawi (2017) provided a systemic account of socio-economic and environmental implications of renewable energy development in Oman. However, the study was mainly focused on one technology type, i.e. solar photovoltaic (PV), focused on the residential sector only and evaluated the socio-economic and environmental implications against one point of time without extending to study the long-term implications. Thus, this chapter investigates the intersection between Oman's electric power sector and economic, social and environmental domains. By so doing, the chapter develops scenarios to assess the long-term implications of renewable energy integrity in Oman's future fuel mix particularly in the electric power sector. System dynamics methodology is employed to build the scenarios and to provide a systemic account for economic, social and environmental implications of renewable energy uptake in Oman.

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[1] Sustainable development in this chapter refers to the definition in the Brundtland Commission Report of 1987: development that meets the needs of the present without comprising the ability of future generations to meet their needs (Brundtland 1987).

2 Oman: Power Sector and Renewable Energy

2.1 Fossil Fuels and Oman's Electric Power Sector (1970s–2018)

The evolution of Oman's electric power system is highly correlated to the discoveries of oil and gas resources since the 1960s. The first power and desalination plant was established in 1975 in Al Ghubra, with an initial capacity of 25.5 MW of electricity and 6 million gallons of desalinated water. The plant was initially fired by diesel before its upgrade in 1980s. That upgrade converted the plant from diesel to natural gas and increased the capacity to 294 MW and 12 million gallons of water. In 1986, due to demand for water that outpaced supply, two new water units were constructed to double the production capacity to 24 million gallons. Initially, the Al Ghubra project principally supplied the capital city (Allen and Rigsbee 2000).

A new Ministry for Water and Electricity Regulation was established in 1978. The new ministry extended the construction of power stations to areas beyond the capital city, including some northern parts of Oman, building a 250 MW station to serve the Rusayl Industrial Estate, the 26.5 MW Wadi Al Jizzi station serving residential sector and a 53 MW station serving a copper refinery and Sohar. Another 22 locations outside the capital city were also supplied with about 27 MW by diesel-powered generation plants (Allen and Rigsbee 2000). The development of the national grid in the 1990s connected the capital city with other distributed generation plants and led to the establishment of new power projects to meet growing electricity and water demands.

In 2005, the Authority for Electricity Regulation was established to undertake the regulation of the newly restructured electricity sector. Likewise, the Public Authority for Electricity and Water was established to handle all of the sector's legal responsibilities, which were previously enacted by the Ministry for Water and Electricity Regulation. Up to 2018, the Authority for Electricity Regulation regulates the electricity sector under the new Sector Law, which was approved by the Council of Ministers in 2004 to oversee the development of regulation and progressive privatisation of the electricity and related water sectors (IBP Inc. 2015).

The new electricity sector consists of three markets: the Main Interconnected System (MIS), which serves the majority of customers residing in the northern part of the county; the rural areas market, which serves rural areas in Oman; and the Dhofar electricity market, which serves the southern part of Oman. Generation, transmission and distribution companies were unbundled under the new electricity market, except for those in the rural electricity market. Under the 2004 law, Oman Power and Water Procurement Company (OPWP) is the only entity that buys electricity from all licensed electricity generation companies under long-term contracts of power purchase, which span 15 years on average, and sells bulk electricity supplies to electricity distribution companies (AER 2008). The Oman electricity distribution market has been monopolised by four licensed, state-owned electricity distribution companies, i.e. Muscat, Majan, Mazoon and Dhofar, that have the right to buy the bulk supply of electricity from OPWP in order to distribute electricity

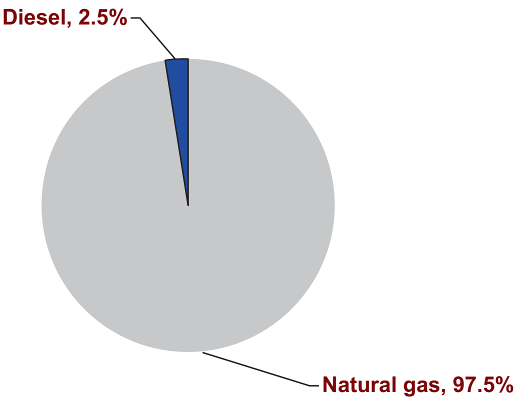

Fig. 2.1 Fuel mix for electric power generation in Oman in 2011. (Source: Author based on data from AER (2011))

within their authorised areas. The legislation stipulates that the electricity distribution companies can only purchase their electricity from the OPWP (Royal Decree 78/2004 2004).

Electricity generation is characterised by high reliance on hydrocarbon-based technologies such as open cycle gas turbine (OCGT) and closed cycle gas turbine (CCGT). The main national grid, i.e. MIS, consists of a total of 11 plants, which generate electricity from natural gas (OPWP 2015). Of those, five are operational OCGT plants with a total generation capacity of 1945 MW and six are CCGT plants with a total generation capacity of 5171 MW (OPWP 2015). The electricity generators purchase their gas requirements from the Ministry of Oil and Gas. The contribution of natural gas in the fuel mix for electricity generation accounted for more than 97% in 2011, while the diesel, which is used in off-grid plants to generate electricity for rural areas or as backup for grid-connected plants during peak periods, contributed just less than 3% (Fig. 2.1) (AER 2011).

2.2 *Rising Energy Challenges*

The high dependence on available natural gas and diesel resources to fire power plants along with highly subsidised fossil fuel-based energy services such as electricity has created new challenges for Oman's power sector. These include energy security, economic vulnerability to oil prices and increasing greenhouse gas emissions.

In a total area of 309,501 km^2, the population of Oman almost doubled from 2.34 million in 2003 to 4.24 million in 2013 (World Bank 2013a). Population growth, the semiarid environment of Oman, the need for air conditioning, the increase in the standard of living, expansion of energy-intensive industrialization, introduction of new households and infrastructure investments and highly subsidised electricity services have been driving the annual growth of power demand by double digits. Oman's annual growth of power demand was projected to be 10% between 2013 and 2020 (OPWP 2014). Meanwhile, the peak power demand is expected to increase at 11% annually in the same period. Since the 2005 market restructuring, the number of electricity accounts has increased by 116.6% (AER 2017), and electricity supply in 2017 reached 32.3 TWh, 240% higher than in 2005 (Fig. 2.2). Residential customers accounted for 46.0% of total supply in 2017, compared to a 55.2% share in 2005. In return, natural gas used for electricity generation has increased from 104.4 billion Scf in 2000 to 295 billion Scf in 2015 (AER 2011; NCSI 2015), and the domestic share of natural gas consumption by the power sector increased from 19.1% in 2000 to 21% in 2014 (NCSI 2015).

Due to the increasing demand on domestic natural gas supplies and because Oman has very small oil and gas reserves compared with other gulf countries along with the country's long-term contracts and commitments to export natural gas, Oman has already started to import natural gas from Qatar via the Dolphin pipeline system since 2008 (EIA, US 2013). Further, Oman has signed a memorandum of understanding with Iran to import gas. Oman's crude oil reserve to production ratio (R/P ratio) is equal to 14 years, and its natural gas R/P ratio is equal to 27 years (IRENA 2016).

Furthermore, the increasing demands on oil and gas for power generation divert the allocation of oil and gas commodity for local use rather than export. Giving Oman's narrow export profile characterised by high proportion of oil and gas, the allocation of oil and gas for domestic use directly impacts Oman's economy which is highly reliant on oil and gas export revenues. This challenge is in line with the economic vulnerability to oil price shocks. In other words, as oil prices rise, the economic revenues go up and so governmental spending on salaries and investments. When the prices decline, and giving Oman's narrow export profile, the state budget is directly impacted and so the governmental spending. Austerity measures to eliminate the negative effects of low oil prices, however, affect the employment

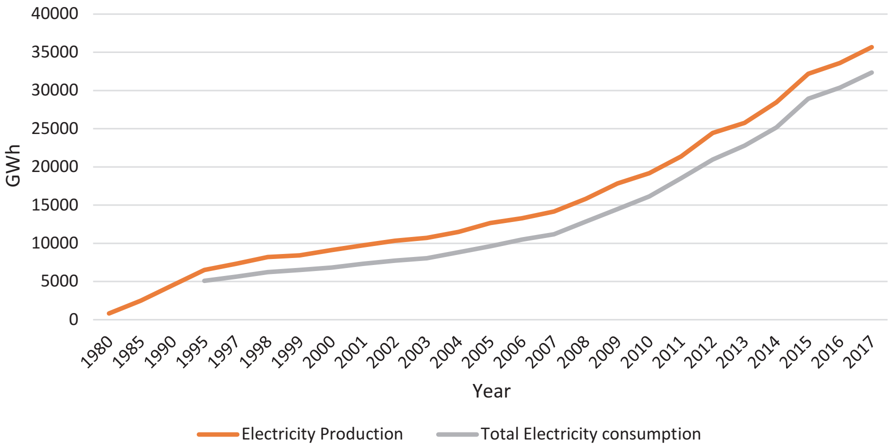

Fig. 2.2 Dynamics of electricity production and consumption in Oman (1980–2017). (Source: Author own with data from Statistical Year Book (NCSI 2012, 2015, 2018))

in both public and private sectors especially that the private sector in Oman is directly connected to the public sector.

Domestic consumption of hydrocarbon resources, mainly oil and gas, has also contributed to incremental increases in Oman's total carbon emissions due to 100% reliance on these resources to meet increasing domestic energy needs. Oman is not a major contributor to global total greenhouse gas (GHG) emissions, but it is ranked among the highest in the world in terms of per capita carbon emissions (World Bank 2013b). In 2013, Oman, for example, was ranked 13th globally in terms of per capita CO_2 emissions (World Bank 2013b). The total greenhouse gas emissions in Oman have increased by 452.28% between 1970 and 2012 and are projected to grow by an average of 5% per year (World Resources Institute 2014). The energy sector accounted for 90% of total GHG emissions in 2014 due to 100% reliance on hydrocarbons, followed by emissions sourced from bunker fuels, industrial activities, agriculture and waste (World Resources Institute 2014). Renewable energy, if managed properly, could provide solution to the aforementioned challenges, i.e. energy security, employment and increasing GHG emissions. Therefore, the purpose of this chapter is to assess the role of renewable energy to address these particular challenges.

2.3 The Current Status of Renewable Energy in Oman

Aware of the arising economic, social and environmental challenges associated with 100% reliance on hydrocarbons, the Omani government has started to pay attention towards developing alternative energy resources such as renewables. In 2008, Oman's Authority for Electricity Regulation launched a study to assess the potential renewable energy resources in Oman. The study indicates the existence of significant renewable energy resources in Oman, especially wind and solar. The AER (2008) study indicates that the solar energy density in Oman is among the highest in the world. The solar insolation varies from 4.5 to 6.1 kWh/m^2 on a daily basis, which corresponds to 1640–2200 kWh per year. The highest potential is concentrated in northern Oman and in desert areas, which cover 82% of the country, while the lowest is in the southern coastal area.

The AER (2008) study identified two solar technologies suited to the environmental conditions in Oman: photovoltaic (PV) systems and solar thermal plants or concentrated solar power (CSP). Under the assumption that 50% of the houses in Oman are suitable for PV installation and that an area of 20 m^2 is available at each house, the same study estimated that the total potential area would provide space for an installation capacity on the order of 420 MW and annual electricity production of 750 GWh (AER 2008). CSP systems, on the other hand, concentrate solar insolation in order to produce steam, converting kinetic power into electricity as in conventional power plants. The advantage of CSP systems is that they store heat recovered during the day for use at night, enabling continuous electricity production. The AER (2008) study indicated that 1 km^2 of land is required to install CSP power plant of 10 MW capacity. Accordingly, if ~280 km^2 of desert area (0.1% of the country's land area) are used to build CSP plants, around 13,900 GWh can be produced (AER 2008). Further, the AER (2008) study identified significant wind energy potential in coastal areas from Masirah to Salalah in Southern Oman and in the Dhofar mountain chain north of Salalah. Theoretically, it is estimated that the installation of 375 wind turbines with 2 MW capacity, 80 m hub height and 90 m rotor diameter in Oman would have a technical generation potential of at least 750 MW and require a wind farm land area of approximately 100 km^2, preferably installed in the available lands in the mountains north of Salalah or at Sur; this corresponds to 20% of the total electricity generation in Oman in 2005 and around 0.03% of the country's land area.

From the above discussion, it appears that if all available solar and wind resources have been harnessed, a total of 3970 MW electricity capacity can be generated from renewables, which corresponds to around 48.2% of total electricity installed capacity in 2018.

The release of a 2008 governmental study was followed by an introduction of two policy initiatives that aim to promote the uptake of renewable energy in Oman. On 16 March 2013, the Authority for Electricity Regulation (AER) announced the first policy to promote the integration of renewable energy in rural area energy systems. The goal of this first renewable energy policy was to promote the integration of renewable energy deployment into the current diesel-based energy system that provides electricity to remote and rural areas (AER 2013). The second policy initiative, locally called the 'Sahim' scheme, was established by Oman's AER in 2017 (Viswanathan 2017). It enables individuals, such as homeowners and institutions, to produce solar electricity for use and surplus sale to electricity distribution companies at the cost of electricity. The present share of renewable energy in total electricity installed capacity is less than 1% (author's calculations).

In addition, in 2017, the Omani government has established a national committee to develop a national energy strategy aiming to investigate the possible integrity of alternative energy sources and reduce the dependence on domestic supplies of oil and gas (Prabhu 2018). The new fuel diversification strategy envisions a 10% share of renewable energy in power generation capacity by 2025, which equals to 2600 MW, 3000 MW use of clean coal by 2030, as well as the use of petcoke and imported gas (Prabhu 2018). Although the strategy has been approved in 2018 (Prabhu 2018), the strategy could benefit from a systemic account of intersection between the power sector and economic, social and environmental domains, which is currently missing. This is important to evaluate the extent at which the integrity of alternative energy sources could address the arising energy issues in Oman (see Sect. 2.2), namely, shortages in natural gas supplies, employment and increasing CO_2 emissions (see Sect. 2.2). Therefore, this chapter positions itself to address this gap in Oman's fuel diversification strategy and aims to provide a systemic account for the intersection between Oman's electric power sector and economic, social and environmental domains. This is useful because it allows policymakers who represent different sectors to see a fuller picture in terms of the potential effects posed by the use of alternative energy sources.

3 Scenario Modelling Approaches

3.1 From Linear to System Thinking

Since the early 1970s, a wide variety of models became available for analysing energy systems or subsystems (such as power systems) due to the sudden oil price increases. The high price of oil emphasised the need for coordinated developments of the energy systems and led to a number of modelling efforts for strategic planning. Since then models have been developed for different purposes – they were concerned with better energy supply system design given a level of demand forecast and better understanding of the present and future demand-and-supply interactions and energy supply planning (Bhattacharyya 2011).

Moreover, the recent challenges of climate change, security of energy supply and economic recession have triggered efforts to investigate the potential role of renewable energy to combat these issues by converting energy systems from dependency on fossil fuels to renewable energy sources (Lund 2007). A crucial element in this transformation is often to show coherent technology analyses of how renewable energy can be implemented and what effects renewable energy has on other parts of the energy system (Connolly et al. 2010). Different computer tools were developed to analyse the integration of renewable energy into various energy systems under different objectives. There are a large number of models from which a selection of scenario modelling tool can be challenging in this research (e.g. see Connolly et al. 2010). To overcome this challenge, it is important to identify clear objectives of the model under question before selecting the relevant modelling tool. Therefore, the following paragraphs provide a discussion of the most relevant modelling tools that can be used to approach the specific objective of modelling exercise for energy policy as discussed in this chapter.

The Brookhaven Energy System Optimization Model (BESOM) is one of the early day applications that was developed at a country level for efficient resources allocation in the USA. The first version of the model was implemented at the national level for a snapshot analysis of a future point in time. Later on, the capability of the model was extended to include a macroeconomic linkage through an input-output table. Further, multiperiod or dynamic models have emerged. Market allocation (MARKAL) is a derivative of the BESOM model. In addition to country specific models, more generic models for wider applications, including MARKAL model, came into existence. The tradition of linking an econometric macroeconomic growth model with an interindustry energy model was pioneered by Hudson and Jorgenson (1974).

In the mid-1980s, the focus was shifted to energy-environment interactions. At this stage, the energy models incorporated environmental concerns more elaborately and the practice of long-term modelling (Bhattacharyya 2011). An example is Teri Energy Economy Environment Simulation Evaluation model (TEEESE) which was used in India for evaluating energy-environment interactions and producing a plan for greening the development process in India (Pachauri and Srivastava

1988). In the 1990s, the focus shifted towards energy-environment interactions and climate change-related issues. During this period, the effort for regional and global models increased significantly and a number of new models came into existence. These include Asian-Pacific Model (AIM), second-generation model (SGM), RAINS-Asia model, Global 2100, DICE, POLES, etc. Existing models like MARKAL saw a phenomenal growth in application worldwide. Similarly, the LEAP model became the de facto standard for use in national communications for the United Nations Framework Convention on Climate Change (UNFCCC) reporting (Bhattacharyya 2011).

These early forms of energy models, however, were mainly linear programming applications based on the optimisation of energy systems. A more comprehensive model that integrates a large number of economic components with respect to MARKAL is the General Equilibrium Model for Energy-Economy-Environment interactions (GEM-E3) (Musango 2012). The GEM-E3 model includes the economic frameworks used by the World Bank (national accounts and social accounting matrix) as well as projections of full input-output tables by country/region, employment, balance of payments, public finance and revenues, household consumption, energy use and supply and atmospheric emissions (Capros et al. 1997). The GEM-E3 model resembles the structure of Threshold 21 (Bassi 2009), a causal-descriptive model, where system dynamics is employed and where society, economy and environment are represented.

Threshold 21 and other system dynamics models are able to combine optimisation and market behaviour frameworks and the investigation of technology development into one integrated framework that represents the causal structure of the system (Bassi 2009; Musango 2012). System dynamics models offer a complementary approach that allows the assessment of renewable energy integration in an energy system while concurrently simulating the interaction of a large number of feedback loops with major factors in the economy, the society and the environment (Musango 2012; Musango et al. 2012). Both scenario analysis and system dynamics approaches consider a higher degree of complexity inherent in systems than the study of individual projects or technologies. They allow the endogenous complexity of energy systems and building future possible pathways into the future to be captured. This provides useful insights for policymaking to evaluate the impacts of alternative energy uptake scenarios. To this end, in this chapter, system dynamics modelling is used as a scenario-modelling tool. A detailed overview of the system dynamics modelling approach is provided in the following section.

3.2 System Dynamics Approach

System dynamics can be defined as a methodology used to understand how systems change over time. The way in which the elements or variables composing a system vary over time is referred to as the behaviour of the system. In the ecosystem example, the behaviour is described by the dynamics of population growth and decline.

The behaviour changes due to changes in food supply, predators and environment, which are all elements of the system (Martin 1997).

A common scientific tool used to investigate patterns and behavioural change over time is modelling. A *model* can be defined as a 'representation of selected aspects of a real system with respect to specific problems(s)' (Barlas 2007). According to this definition, we do not build models of systems, but we build models of specific aspects of systems to study specific problems.

Therefore, *system dynamics* modelling is an approach used to study the behaviour of complex systems. It aims to demonstrate how policies, decisions, structures and delays are interrelated and influence growth and stability. The interrelationships create structure, which in turn produces behaviour (Lee and von Tunzelmann 2005). Sterman (2000) suggests that dynamic complexity arises because systems are dynamic, non-linear, tightly coupled, governed by feedback, history dependent, self-organising, adaptive, counter-intuitive, policy-resistant and characterised by trade-offs, etc. Dynamic complexity arises from the interaction between agents over time. System dynamics is also a problem-solving approach that involves models and simulations that examine a variety of relationships between the components of any dynamic processes (Sterman 2000).

One major advantage of models is to try things out and analyse their consequences, including experiments that would be impossible, impractical or unethical with a real system or in system configurations that do not (yet) exist. For instance, studying energy systems often involves recommending alternative policy options that can steer the system towards more sustainable modes. Models can be used to experiment with the consequences associated with implementing alternative policy options. Such experimentation in the real world might involve time delays and/or great expense. Also, some alternative policy options may have unperceived negative social effects that can be avoided through modelling practices (Sterman 2000).

System thinking advocates stress that the world is a complex system, in which we understand that 'everything is connected with everything else' in such a way that 'you cannot just do one thing'. This implies that if people had a holistic view of the world, they would then act in consonance with the long-term best interests of the system as a whole (Sterman 1994). The feedback loop character of system dynamics accounts as a concept to aid decision-making processes. In reality, we make decisions to alter the real world; we receive information feedback about the real world, and, using the new information, we revise our understanding of the world and the decisions we make to bring the state of the system closer to our goal (Fig. 2.3).

System dynamics modelling approach offers a tool that can capture and address the short-term and long-term impacts of decision-makers on the real world. In general, the advantage of using system dynamics models is their ability to integrate systematically the knowledge about variables and processes of the analysed system and to let their interactions generate a phenomenon of interest. With explicit assumptions and clarity of causal factors, these models can generate an understanding of the operating mechanisms under question.

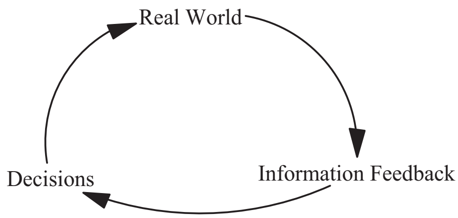

Fig. 2.3 Feedback process in decision-making. (Sterman 2000)

4 Methodology: Development of the Dynamic Model

System dynamics methodology was used to develop four scenarios of renewable energy share in Oman's future energy mix. System dynamics is a methodology, originally developed by Jay Forrester and his colleagues at Massachusetts Institute of Technology (MIT) in the 1950s. Computer simulation models are used to develop models that enable better understanding of complex systems and their dynamic behaviour under a given set of conditions or scenarios so that to avoid potential negative consequences or prepare for them (Sterman 2000; Ford 2009). In this methodology, the dynamic behaviour of the system is assumed to be a result of interconnected web of feedback loops. Feedback loops are illustration of connection between variables, which define a system under question, with causal links. They are of two types: positive (also known as reinforcing) and negative (also known as balancing). Positive feedback loops enhance or amplify the feedback of information. Negative feedback loops are goal seeking and tend to resist change in the system.

Vensim software was used to build the scenarios in this research. Vensim allows to explore the dynamical behaviour of the system once the variables are identified and connected, feedback loops are recognised and the model is ready for simulation. In this study, there are two subsequent steps that were used in order to develop the simulation models using Vensim software. These are causal loop diagrams and followed by stock-and-flow models based on the modelling process of Ford (2009) and Wolstenholme (1990). Once the stock-and-flow models were designed, the simulation equations were built in order to connect the variables that identify each model in concern.

4.1 Data Sources

Oman's high dependence on oil and gas over the last four decades has been associated with unprecedented challenges such as energy security, employment and increasing CO_2 emissions (see Sect. 2.2). In this study, these criteria formulate a foundation for the model structure.

Quantitative data were collected from different secondary sources including Omani governmental documents such as statistical yearbooks issued by the National

Center for Statistics and Information, Oman; annual transmission capability statement reports prepared by the Oman Electricity Transmission Company; the Oman Power and Water Procurement Company (OPWP) 7-year statement reports; annual reports issued by the Authority for Electricity Regulation; and other electronic database like World Bank, US Energy Information Administration (EIA), International Energy Agency (IEA), World Resources Institute (WRI), BP Statistical Review of World Energy and International Monetary Fund (IMF).

4.2 Setting the Scenarios

In order to enable estimating the future effects associated with the deployment of different renewable energy technologies in Oman's economic-environmental-social contexts, a starting point involved formulating four scenarios for future renewable energy deployment in Oman. Given that the maximum power that can be harnessed from solar and wind resources account potentially for 48.2% of total electricity installed capacity in 2018 (see Sect. 2.3), three renewable energy integrity scenarios are proposed along with a business-as-usual scenario. These scenarios assume different trajectories of solar PV, CSP and wind share in Oman's future total electricity installed capacities (Table 2.1), as follows:

- Business-as-usual scenario implies that there is no promotion for renewable energy policies or implementation of any renewable energy action plans.
- Moderate scenario implies 10% of electricity generation is sourced from renewable energy sources through 2040.
- Advanced scenario implies 30% of electricity generation is sourced from renewable energy sources through 2040.
- Ambitious scenario implies 50% of electricity generation is sourced from renewable energy sources through 2040.

A starting point to build the scenario models was to define a conceptual framework that informs the structure of the model under question. As discussed in Sect. 2.2, energy security, reduction of CO_2 emissions and job creation were defined as the most important factors to promote the uptake of renewable energy in Oman (Fig. 2.4). These factors formulated boundaries for this research's model and informed the build of an overall conceptual framework which was used to build an

Table 2.1 Scenarios for renewable energy deployment pathways through 2040

	Scenario assumptions				
Scenario name	Solar PV	Solar CSP	Wind	Total RE	FF
BAU	0%	0%	0%	0%	100%
Moderate	2%	3%	5%	10%	90%
Advanced	10%	10%	10%	30%	70%
Ambitious	10%	20%	20%	50%	50%

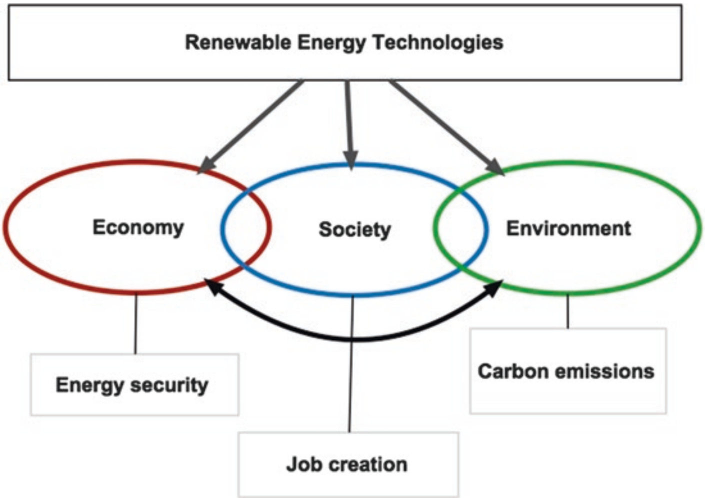

Fig. 2.4 A conceptual framework shows the potential contribution of renewable energy technologies to energy security, job creation and carbon emissions reduction which represent economic, social and environmental domains, respectively

aggregated model structure for scenario analysis for future uptake of renewable energy in Oman. In this conceptual framework, the identified policy indicators have been classified under three main domains: economic, environmental and social. Energy security, for example, is set under the economic domain. This, in turn, interacts with another two domains: social and environmental domains. Under the social domain, job creation is considered as the main criterion that represents this domain. The environmental domain considers carbon emissions for further assessment. Energy security, carbon emissions and job creation are selected as policy indicators against which the performance of scenarios will be evaluated.

4.3 Feedback Loops Representing Intersection Between Oman's Power Sector, Economic, Social and Environmental Domains

The use of system dynamics methodologies to build the scenario models comprises two main steps: (i) identifying the main feedback loops in the system and (ii) identifying the stock-and-flows in the system.

In this section, the main feedback loops that represent the intersect between Oman's power sector and economic, social and environmental domains are identified and presented in Fig. 2.5. The development of the main feedback loops was guided by the conceptual framework presented in Fig. 2.4.

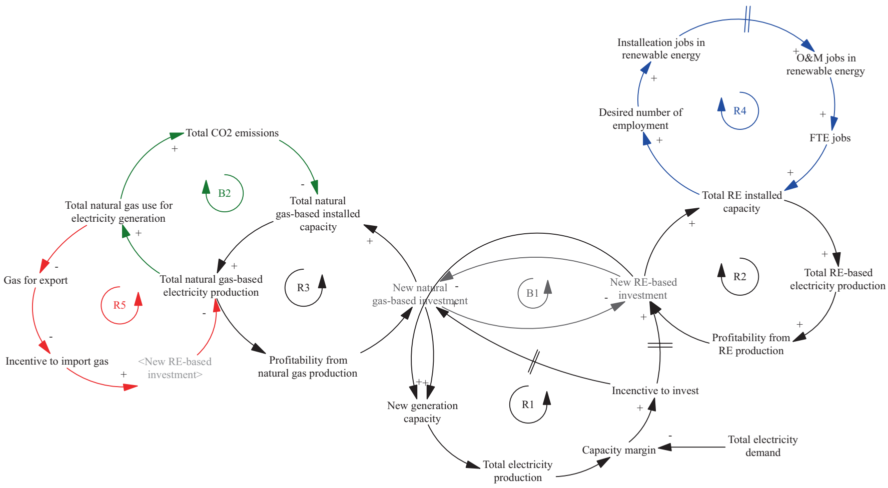

Fig. 2.5 Presentation of important feedback loops that represent the dynamic behaviour of Omani energy system

The main assumption of the overall causal loop diagram (Fig. 2.5) is that increasing share of renewable energy investments decreases the share of natural gas-based investments (B1), which represents a balancing relationship. Thus, the balancing causal loop (B1) represents the interaction between the new renewable energy investments and new natural gas-based investments. R2 causal loop indicates a reinforcement loop for total electricity production from renewables. That is, the larger the investments aimed to increase the renewable energy capacity, the larger electricity production from renewables and hence renewable energy profitability (R2). Similarly, R3 causal loop suggests that the larger the investments aimed to increase natural gas-based capacity, the larger electricity production from conventional sources and hence natural gas-based profitability.

The three modelled domains, i.e. economy, society and environment, with which renewable energy interacts are illustrated in red, blue and green, respectively (Fig. 2.5, also see Fig. 2.4). The economic domain (in red) is represented by one reinforcing loop, R5. As electricity generation from natural gas-based technologies increases, the demand for natural gas in power sector increases, leading to decline in commodity allocated for export, incentivising natural gas imports, which in return creates an incentive to invest in renewables to enhance energy security (Fig. 2.5, R5). The social domain (in blue) is represented by one reinforcing loop, R2. As total renewable energy installed capacity increases, the desired number of jobs in the new sector increases which in return leads to creation of job in both installation and operation and maintenances stages of project life cycle (Fig. 2.5, R2). The environmental domain (in green) is represented by one balancing loop, B2. As electricity generation from natural gas-based technologies increases, natural gas consumption by the power sector increases, leading to total increase in CO_2 emissions which in return disincentivises investments in natural gas-based technologies and hence incentivises the search for clean energy sources (Fig. 2.5, B2).

5 Components of the Dynamic Model: Stock-and-Flow Diagrams

This section presents the main stock-and-flow diagrams that informed the analysis of renewable energy impacts on social, economic and environment domains under different scenarios proposed in Sect. 4.2. A starting point for the model development was to simulate the supply and demand of Oman's main national grid power system. This is important to forecast the future energy demand as well as future desired installed capacity, through 2040 as per this chapter. Therefore, supply and demand sub-model were designed (Fig. 2.6).

The supply and demand sub-model consist of two stocks: annual electricity demand and total installed capacity. The annual electricity demand (ED) increases by changes in electricity demand, which is determined by the electricity demand growth rate. Total installed capacity (IC), on the other hand, is determined by the investments in the power sector. Investments in the power sector result from the desired capacity adjustment, which equals to capacity margin. Capacity margin (CM) is calculated, as follows:

$$CM = (IC - ED) / ED \tag{2.1}$$

The forecast of desired installed capacity is necessary because it enables to estimate the future share of renewable energy in total power generation capacity. In this way, it is possible to connect energy security, employment and CO_2 emission sub-models systematically. These sub-models are explained, as follows.

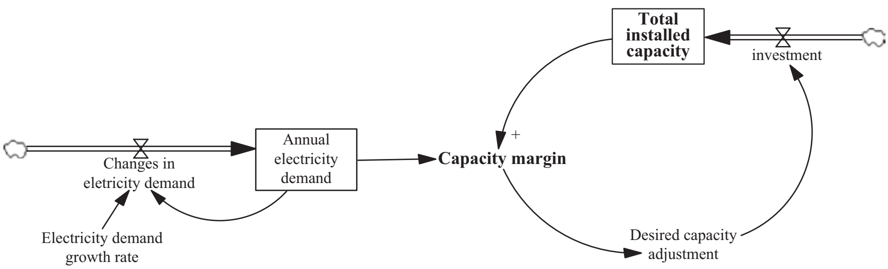

Fig. 2.6 Supply and demand sub-model

5.1 Energy Security Sub-model

Natural gas is the main fuel used to generate electricity for Oman's main national grid. For the main national grid, open cycle gas turbine or combined cycle gas turbine power technologies are the main two types of gas-fired power-generating technologies (see Sect. 2.1). The sub-model for natural gas use, therefore, calculates the total amount of natural gas used to generate electricity for the main national grid in Oman under different renewable energy integrity scenarios (Fig. 2.7). This sub-model evaluates the influence of renewable energy integrity on natural gas consumption.

The energy security sub-model consists of three stocks: FF installed capacity, total FF electricity production and total natural gas use in BTU.

FF installed capacity (FFIC, in MW) increases by FF investment growth (G_{FFI}, in MW/year) and decreases by depreciation rate (DR, in MW/year), as follows:

$$\mathrm{FFIC} = \mathrm{FFIC}\left(21354^{*}1e+06\right) + \int\left[G_{\mathrm{FFI}} - \mathrm{DR}\right]dt \tag{2.2}$$

FF investment growth (G_{FFI}, in MW/year) is calculated by multiplying FF investment growth rate ($\mathrm{GR}_{\mathrm{FFI}}$, in fraction/year) by total installed capacity (IC, in MW):

$$G_{\mathrm{FFI}} = \mathrm{GR}_{\mathrm{FFI}}{}^{*}\ \mathrm{IC} \tag{2.3}$$

Depreciation rate (DR, in MW/year), on the other hand, is calculated by dividing the FF installed capacity (FFIC, in MW) by average technology life (ATL, in years):

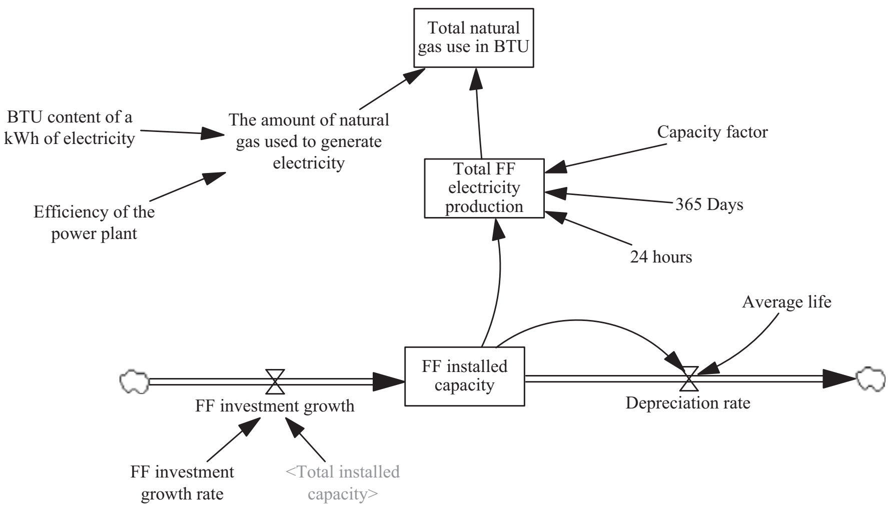

Fig. 2.7 Stock-and-flow diagram for energy security sub-model

$$DR = \frac{FFIC}{ATL} \tag{2.4}$$

Total FF electricity production (FFEP, in kWh) is calculated from multiplying FF installed capacity (FFIC, in MW) by capacity factor (CF, in 0.48) by 356 days by 24 hours, as follows:

$$FFEP = FFIC^{*} CF^{*} 365\,Days^{*} 24\,Hours \tag{2.5}$$

Therefore, the natural gas use in BTU is quantified from multiplying total FF electricity production (TFFEP, in MWh) by the amount of natural gas used by power plant to generate 1kWh of electricity (NG_{kWh}, in BTU/kWh), as follows:

$$NGU_{BTU} = TFFEP^{*}\, NG_{kWh} \tag{2.6}$$

The amount of natural gas used by power plant to generate 1 kWh of electricity depends on the efficiency or heat rate of the power plant and the heat content of the fuel. The heat rate is a measure of the efficiency of a generator and is simply the amount of energy used by an electrical power plant to generate 1 kWh of electricity. The amount of natural gas used by power plant to generate 1 kWh of electricity is thus calculated by dividing the BTU content of a kWh of electricity (BTU_{kWh}, in BTU/kWh) by the efficiency of the power plant (E_{NG}, in %) as follows:

$$NG_{kWh} = BTU_{kWh} \,/\, E_{NG} \tag{2.7}$$

The parameters and input variables for the energy security sub-model are presented in Table 2.2.

5.2 *Employment Sub-model*

Renewables contribute to the creation of direct, indirect and induced jobs. The term direct jobs refers to jobs related to core activities such as manufacturing, fabrication, construction, site development, installation and operation and maintenance (O&M) (Wei et al. 2010). On the other hand, indirect jobs refer to the jobs created within the supply chain supporting a specific renewable energy project such as

Table 2.2 Parameters used in energy security sub-model

Parameter	Type	Value	Unit	Notes/source
BTU content of a kWh of electricity	Constant	3412	BTU/kWh	US EIA website
Efficiency of power plant	Constant	52	%	American Electric Power
Power plant capacity factor	Constant	48	%	US EIA website
Average life of power plant	Constant	20	Year	Estimated

extraction and processing of raw materials and the administration at ministries. Induced employment commonly refers to jobs created as a result of economic activities of direct and indirect employees. The wages paid to direct and indirect employees are spent on goods and service, supporting further employment. In this study, however, only direct jobs are calculated. The calculation of indirect jobs is considered not applicable because renewable energy technologies are not created locally but imported. Likewise, given the fact that detailed knowledge of how industries link to one another is required and nascent development of renewable energy in Oman, the evaluation of induced jobs remains a difficult task.

In order to determine the number of direct jobs that can be created as a result of establishing different types of renewable energy power plants in Oman, the job creation sub-model was designed (Fig. 2.8).

The job creation sub-model consists of two stock variables: capacity under construction and operational generation capacity; and three flows: construction rate, completion rate and ageing rate. Thus, the stock of capacity under construction (CUC, in MW) increases by construction rate (CNR, in MW/Year) and depletes by completion rate (CMR, in MW/Year). Similarly, operational generation capacity (OGC, in MW) increases by completion rate (CR, in MW/Year) and decreases by ageing rate (AR, in MW/Year), as follows:

$$\text{CUC} = \text{CUC}(0) + \int[\text{CNR} - \text{CMR}]\,dt \tag{2.8}$$

$$\text{OGC} = \text{OGC}(0) + \int[\text{CR} - \text{AR}]\,dt \tag{2.9}$$

The creation of renewable energy installation jobs is associated with the project construction. Therefore, the number of renewable energy installation jobs is calculated by multiplying capacity under construction (CUC, in MW) by the installation employment factor (IEF), as follows:

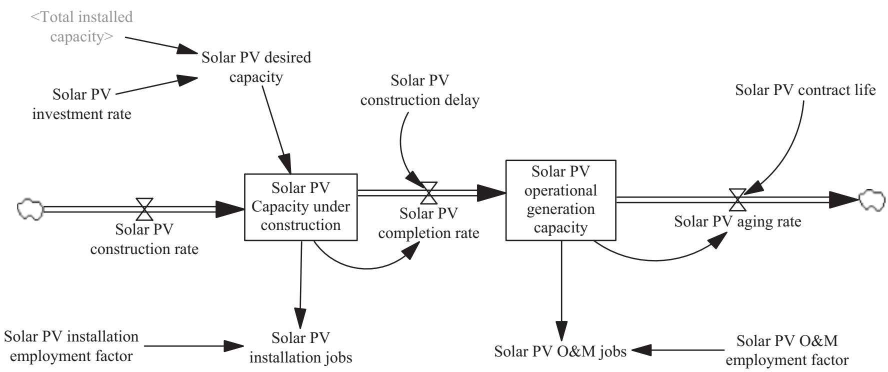

Fig. 2.8 The stock-and-flow diagram of job creation sub-model. Solar PV sub-model is shown for illustration

Table 2.3 Parameters used in job creation sub-models for three types of technologies: solar PV, CSP and wind technology

Parameter	Type	Value	Unit	Notes/Source
Solar PV O&M employment factor	Constant	0.3	Jobs/MW	(Blyth et al. 2014)
Solar PV installation employment factor	Constant	13.2	Jobs/MW	(Blyth et al. 2014)
Solar CSP O&M jobs/MW	Constant	0.5	Jobs/MW	(Blyth et al. 2014)
Solar CSP installation employment factor	Constant	10.2	Jobs/MW	(Blyth et al. 2014)
Wind O&M employment factor	Constant	0.2	Jobs/MW	(Blyth et al. 2014)
Wind installation employment factor	Constant	1.3	Jobs/MW	(Blyth et al. 2014)

$$\mathrm{IJ} = \mathrm{CUC} \times \mathrm{IEF} \tag{2.10}$$

Similarly, the creation of renewable energy operation and maintenance (O&M) jobs is associated with the project operational generation capacity. Therefore, the number of renewable energy O&M jobs is calculated by multiplying operational generation capacity (OGC, in MW) by the O&M employment factor (OMEF), as follows:

$$\mathrm{OMJ} = \mathrm{OGC} \times \mathrm{OMEF} \tag{2.11}$$

Based on the above stock-and-flow diagram structure, which represents the solar PV technology only, three job creation sub-models for three types of renewable energy technologies are explored and developed in this chapter (i.e. PV, CSP and wind technologies). The parameters that represent the values for each technology type are shown in Table 2.3. Given the fact that renewable energy development in Oman is relatively nascent, employment factors, which vary by technology as well as location, are not available for Oman. Therefore, employment factors identified in Blyth et al. (2014), which apply to European countries that have different macroeconomic conditions than Oman, are used for the purpose of exploring possibilities for Oman.

5.3 CO_2 Emission Sub-model

The reduction of natural gas consumption under different scenarios, as quantified in in the energy security sub-model, has environmental advantages in terms of reducing CO_2 emissions. The quantification of natural gas use under different scenarios enables the quantification of the amount of CO_2 emissions generated under different scenarios due to renewable energy integrity. The CO_2 emission sub-model, therefore, calculates the reduction of CO_2 emissions as a result of reducing natural gas used to generate electricity under different scenarios of renewable energy integrity (Fig. 2.9).

The CO_2 emission sub-model (Fig. 2.9) consists of two stocks: total natural gas use in mmBTU (NGU_{BTU}) and total CO_2 emissions ($\mathrm{Emissions}_{CO_2}$, in kg). The stock

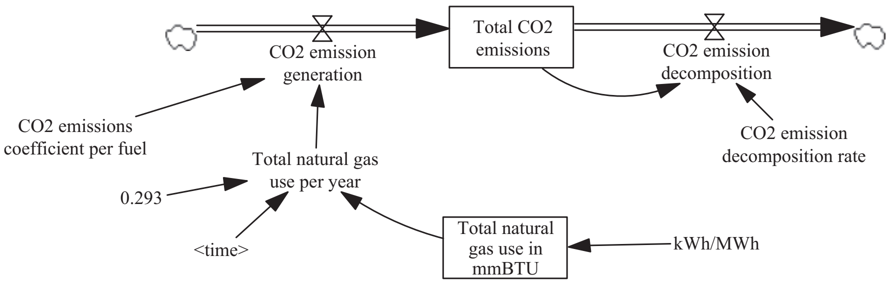

Fig. 2.9 The stock-and-flow diagram of the air emission sub-model

of total natural gas use in mmBTU (NGU_{mmBTU}) has been already identified and quantified in the energy security sub-model (see Sect. 5.1).

The stock of total CO_2 emissions ($Emissions_{CO_2}$, in kg) has two flows, inflow of CO_2 emission generation ($Generation_{CO_2}$ in kg/year) and outflow of CO_2 emission decomposition ($Decomposition_{CO_2}$ in kg/year). Thus, the stock of total CO_2 emission is increased by CO_2 emission generation ($Generation_{CO_2}$ in kg/Year) and decreased by CO_2 emission decomposition ($Decomposition_{CO_2}$ in kg/Year), as follows:

$$\begin{aligned} \text{Emissions}\,CO_2 &= \text{Emissions}\,CO_2\left(1.8652e+10\right) \\ &+ \int\left[\text{Generation}_{CO_2} - \text{Decomposition}_{CO_2}\right]dt \end{aligned} \quad (2.12)$$

CO_2 emission generation ($Generation_{CO_2}$ in kg/year) is determined by multiplying CO_2 emission coefficient per fuel (in kg/MWh) by total natural gas use per year ($TNGU_{mmBTU}$, in mmBTU/year), by the factor 0.293, which converts the NGU_{mmBTU} value from mmBTU to MWh and is given as:

$$\text{Generation}_{CO_2} = CO_2\ \text{Emissions Coefficient} \times NGU_{mmBTU} \times 0.293 \quad (2.13)$$

The parameters and input variables for the CO_2 emission sub-model are presented in Table 2.4.

6 Socio-economic and Environmental Implications of Renewable Energy Integrity in Oman

The performance of renewable energy scenarios in relation to economy, environment and society are discussed as follows.

Table 2.4 Parameters used in CO_2 emission sub-model

Parameter	Type	Value	Unit	Notes/source
CO_2 emission coefficient	Constant	181.08	kg /MWh	US EIA website
Emission decomposition rate	Constant	0.1%	Fraction/ year	Assumed
Total CO_2 emission initial value	Constant	1.8652e+10	kg	World Resources Institute

6.1 Energy Security

A major concern in low-carbon energy transitions is their implication to energy security. In this study, the use of renewable energy, namely, solar and wind, proved to enhance energy security via replacing the use of natural gas to meet the increasing power demands.

In the business-as-usual scenario, wherein no renewable energy is integrated, the use of natural gas for electricity generation was expected to increase by 28% by 2050 compared with 2010. On the other hand, the use of natural gas declined in all other three scenarios compared with the business-as-usual scenario (Eqs. 2.6 and 2.7) due to increase of the share of renewable energy in power generation. Under the moderate scenario, natural gas use was reduced by almost 27% in 2040 compared to the business-as-usual scenario; the advanced scenario suggests a decline by almost 46% in 2040; and over 64% reduction is estimated by the ambitious scenario in 2040, compared to the business-as-usual scenario (Table 2.5 and Fig. 2.10).

6.2 Employment

The simulation output for the social indicator is presented in Fig. 2.11. Given the increase in the renewable energy share in the moderate, advanced and ambitious scenarios, the employment in installation and operation and maintenance of renewable energy technology increases correspondingly (Eqs. 2.10 and 2.11).

Solar CSP provides the largest number of jobs over time compared with other technologies, namely, solar PV and wind technologies. Since there is no installation of renewable energy technologies in Oman in 2018, the total number of jobs is proposed to steadily increase after 2018 through 2040 (Fig. 2.11). Since there is no deployment of renewable energy in the business-as-usual scenario, there are not any jobs associated with renewable energy technologies in this scenario. However, the deployment of renewable energy technologies may adversely impact the number of jobs provided by the fossil fuel sector. This calculation, however, is not included in our models since it goes beyond the aims of this chapter.

For all types of technologies, ambitious and advanced scenarios suggest more installation and O&M job creation compared to the moderate scenario due to the increasing share of renewable energy in the power generation. Yet, in all scenarios,

Table 2.5 Average reduction of natural gas use in power generation under different scenarios compared to business-as-usual scenario

Scenario	2020	2030	2040
Moderate	−10%	−24%	−27%
Advanced	−17%	−40%	−46%
Ambitious	−24%	−56%	−64%

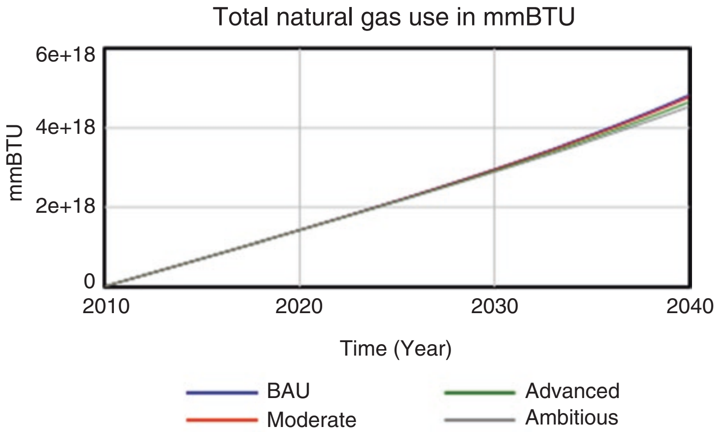

Fig. 2.10 Projection of natural gas use in power generation under four scenarios in 2010–2040

the installation jobs decline due to the end of the power plant construction period (Eqs. 2.8 and 2.10). Operation and maintenance jobs, on the other hand, start to increase by the completion of power plant construction but start to decline due to the ageing of the power plant (Eqs. 2.9 and 2.11) (Fig. 2.11).

6.3 CO_2 Emissions

All scenarios show a steady upwards trend in the total CO_2 emissions produced from electricity generation through 2040 (Eqs. 2.12 and 2.13). The reason is that, in all scenarios, natural gas continues to constitute a proportion of electricity generation mix.

The business-as-usual scenario, wherein no renewables are considered in electricity generation, shows the highest exponential growth in the total CO_2 emissions through 2040, compared with all other scenarios. In this scenario, under the current growth rate of natural gas consumption for power generation, the total CO_2 emissions are expected to rise by 400% in 2040 if no renewables are developed.

All other scenarios, on the other hand, contribute to a relative reduction in total CO_2 emissions sourced from power generation because of the integration of renew-

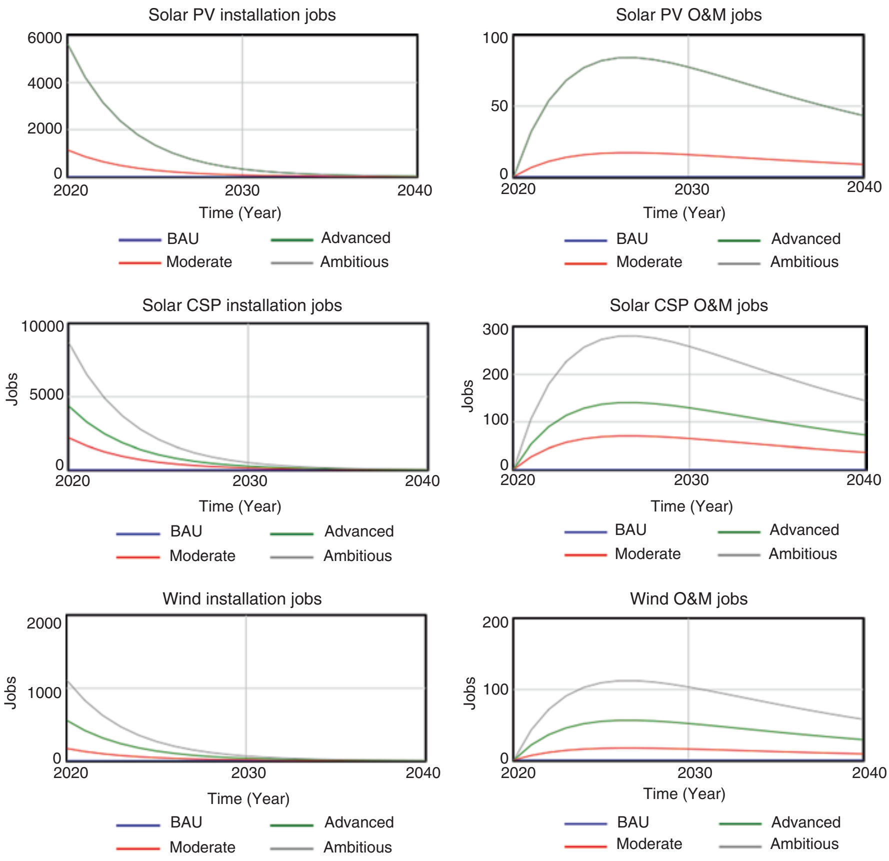

Fig. 2.11 Total number of installation and O&M jobs per year created by each type of renewable energy technology 2020–2040

able energy technologies (Table 2.6 and Fig. 2.12). In the moderate scenario, wherein the share of renewable energy accounts for 10% of total power generation, the total CO_2 emissions are reduced by more than 20% in 2040, compared to the business-as-usual scenario. The advanced scenario shows a reduction of the total CO_2 emissions by over than 40% in 2040, compared to the business-as-usual scenario.

The ambitious scenario, on the other hand, shows a major reduction in total CO_2 emissions compared with the other scenarios due to the dominance of renewable energy technologies in the power generation. About 58% of this reduction is achieved using 10% solar PV, 20% solar CSP and 20% of wind turbine technologies as well as reducing the natural gas use by more than 60% in 2040, compared to the business-as-usual scenario (Table 2.6 and Fig. 2.12).

Table 2.6 Percentage of CO_2 emission reduction by scenario compared to BAU scenario

Scenario	2020	2030	2040
Moderate	−12%	−23%	−25%
Advanced	−7%	−32%	−41%
Ambitious	−9%	−45%	−58%

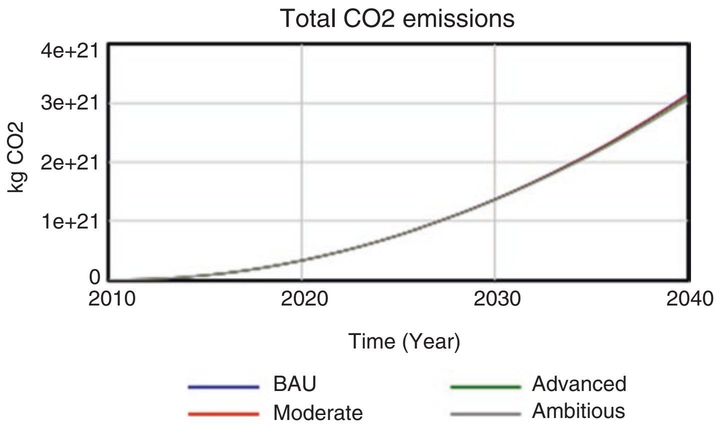

Fig. 2.12 Total CO_2 emissions (in kilogrammes) resulting from natural gas used for power generation in Oman through 2050 under four scenarios

7 Model Verification and Validation

System dynamics models need to be subjected to two types of tests: structural validity tests and behavioural validity tests (Barlas 1989). Structural validity tests aim to determine whether the structure of the model is an acceptable representation of the actual system structure. Behaviour validity tests aim to determine whether the model is able to produce an output behaviour that is close enough to the behaviour of the actual system.

7.1 *Structural Validity Tests*

Four tests were conducted to validate the structure of the model: boundary adequacy, structure verification, dimensional consistency and parameter verification (Qudrat-Ullah and Seong 2010). These are discussed in detail, as follows.

Boundary adequacy and structure verification tests were conducted during the initial stage of model development, i.e. the development of conceptual model. In terms of boundary adequacy, energy security, reduction of CO_2 emissions and job creation were defined as the most important variables which formulate the boundary of this chapter's model (see Sect. 2). Thus, all variables associated with energy security, reduction of CO_2 emissions and job creation were generated endogenously (see Fig. 2.5). Energy demand was the only exogenous variable (see Fig. 2.5).

For the structure verification of our model, country-specific data of Oman was utilised to construct the model (see Sects. 2, 4.1 and 4.2). The conceptual model is represented by a causal loop diagram, as depicted in Fig. 2.5. The causal relationships developed in the model were based on the available knowledge about the real system (see Sect. 4.3).

Furthermore, two tests were conducted during the stage of model's stock-and-flow development (see Sect. 5). These are dimensional consistency and parameter verification. Dimensional consistency test requires that each mathematical equation in the model be tested if the measurement units all the variables and constants involved are dimensionally consistent (Qudrat-Ullah and Seong 2010). Dimensional consistency of each of the mathematical equations used in the model was checked. For instance, Eq. 2.5 was used to calculate the annual electricity production, as follows:

$$\text{FFEP} = \text{FFIC}^{*}\text{CF}^{*}\,365\,\text{Days}^{*}\,24\,\text{Hours}$$

This equation suggests that annual fossil fuel-based electricity production (FFEP) is dependent on two factors: (i) FF installed capacity (FFIC) and (ii) capacity factor (CF). To ensure dimensional consistency, the value of FFIC was estimated based on the installed capacity of natural gas-based electricity in Oman (in MW) over a period of time equals to a year (in days/year multiplied by hours/days). The capacity factor of natural gas-based power plants in Oman was estimated at value of 0.48 (dimensionless). Thus the dimensional analysis of the equation above is:

$$\text{MWh / Year} = \text{MW}^{*}\,(\text{dimensionless}) * (\text{days / Year}) * (\text{hours / days})$$

To ensure parameter verification, the values assigned to the model parameters were sourced from the existing knowledge and numerical data from Oman's case (see Sect. 4.1, Tables 2.2 and 2.4). In some cases, however, where Oman's specific data were not available, external sources of data were utilised to serve the quest of the model. Employment factor is one example of such external data (see Table 2.3).

Based on these tests, the structure of the model was deemed appropriate.

7.2 Behavioural Validity Tests

To ensure behavioural validity and to build on the confidence gained from the validity of the model structure, two transient behaviour tests were carried out to measure how accurately major behavioural patterns in the real world can be reproduced by the model. According to Barlas (1996), the use of graphical or visual measures of typical behaviour features is adequate to validating a model in terms of behaviour.

Firstly, since the modelling was carried out using the Vensim software, the extreme condition testing provided by its ‘reality check’ feature was used. In this process all ‘if/then’ statements according to the relationships between variables are compared with the model simulations, and their conformance with the anticipated behaviour based on the model is checked (Gallati 2008), and this shows a conformance with the conceptual model.

Secondly, in the scenario description, we demonstrated that the trajectories for the base scenario remains essentially unchanged under different iterations, for example, in the employment sub-model (see Sect. 6.2) where there are substantial changes to the social indicators under different scenarios, the base scenario remains the same. This sensitivity analysis shows that the typical behaviour features of the model are valid enough for results to be communicated based on the model simulation. Therefore, once the model was operational, validity tests were conducted to compare the model-generated behaviour to the observed behaviour of the real system. Comparing the output data from a system dynamics-based simulation model with corresponding data from the real world can be done in different ways (Barlas 1989; Qudrat-Ullah 2008). In this chapter, the mean square error (MSE) analysis and the root mean squared percent error (RMSPE) were used to evaluate the behaviour of the model. The MSE provides a measure of the total error, and the RMSPE provides a normalised measure of the magnitude of the error. The simulation of the model started from 2010, providing 8 years of simulated data to compare to the actual behaviour of the electricity demand in Oman (Fig. 2.13). The error analyses in terms of the MSE and the RMSPE were 0.00039561 and 3%, respectively. The RMS percent error of 3% means that the variable replicates the behaviour accurately, an indication of high confidence in the model.

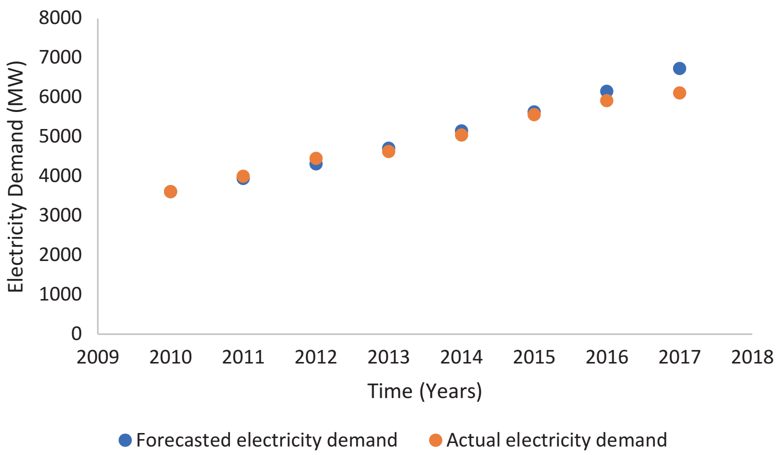

Fig. 2.13 Forecasted and historic electricity demand, Oman

8 Conclusions

This chapter provided a specific focus on building a methodological basis for environmental and macroeconomic impacts of renewable energy deployment in Oman. The developed scenarios are promising to inform the future impacts of renewable energy deployment in Oman as well as supporting renewable energy policymaking in Oman.

The assessment of prospective long-term impacts of renewable energy uptake in Oman in relation to the domains of environment, economy and society has been achieved by developing four scenarios in order to bring about different insights into the possible transition pathways for renewable energy uptake in Oman to 2040. The first scenario, business-as-usual, was used as a reference scenario in which no renewables are considered. The second scenario, the moderate scenario, considers a 30% share of renewable energy in electricity generation by 2040. The third and fourth scenarios consider 50% and 70% shares of renewable energy in electricity generation by 2040, respectively.

The scenarios were developed through two steps: causal loop diagrams, followed by stock-and-flow sub-models. Causal loop diagrams revealed the interlinkage between renewable energy technology deployment and environmental, economic and social domains which represented the carbon emissions, energy security and job creation policy indicators, respectively. In order to enable the simulation of causal loop diagrams, three stock-and-flow sub-models have been developed – air emissions, natural gas saving and job creation – against which the performance of the scenarios was measured.

Based on the simulation results for long-term energy scenarios, the following conclusions can be drawn:

- It was determined that the dominant factors affecting the promotion of renewable energy in Oman are the economic indicators of gas savings, an environmental indicator of total CO_2 emissions and a social indicator of job creation. These factors influence the government's desire to invest in renewable electricity generation.
- The economic indicator analysis ascertained that Oman's reliance on fossil fuel-based electricity may bring future challenges in the event of substantial increases in electricity demand, the limited availability of domestic fossil fuel resources and substantial energy import price increases. Instead, renewable energy deployment can enhance the economy, either through the security of energy supply by saving fossil fuel resources for future use or through freeing natural gas resources used in power generation for export sales or other uses like industrialisation.
- The simulation analysis of environmental indicators suggests that policymakers should consider future mitigation of adverse environmental consequences that might emerge from continuous use of fossil fuel resources in power generation, as illustrated in the CO_2 emission scenarios.

- The simulation analysis of social indicators suggests that there is a need to consider the deployment of alternative energy sources like renewables due to the potential number of green jobs that can be created throughout the renewable energy life cycle.

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